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Measurement of Electromagnetic Properties of Composite Materials

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NAVAL COMMAND, CONTROL AND
OCEAN SURVEILLANCE CENTER
RDT&E DIVISION
San Diego, California 92152-5001

J. D. FONTANA, CAPT, USN
Commanding Officer

R. T. SHEARER
Executive Director

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Released by
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Branch

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K. J. Kochanski, Head
Communications Systems
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INTRODUCTION

The electromagnetic (EM) properties of radome material can greatly affect the performance of the enclosed radars. Radiation characteristics such as power transfer, beamwidth, sidelobe level, and boresight gain can degrade considerably, depending on the type of materials used for the radome. Before any design can be initiated, it is necessary to know the EM properties of the radome material, particularly permittivity and loss tangent. This is particularly important when dealing with composites because of wide variations in the materials received from different suppliers and sometimes even in different samples from the same batch. This report describes four different techniques that may be used for measuring composite materials. Experimental data obtained from each method are presented. Additionally, the advantages and disadvantages of each method are discussed, along with recommendations for future work. The materials selected for measurements are off-the-shelf candidates for use in a composite mast for Navy surface ships.

MEASUREMENT TECHNIQUES

PARALLEL PLATE

The parallel plate method is the most commonly used method for characterizing dielectric materials at low frequencies, typically below 100 MHz. In this procedure, a parallel plate capacitor, which acts as a dielectrically loaded waveguide resonator, is the device under test. Figure 1 shows the model that can be used to relate the real part of permittivity (ϵ') and loss tangent ($\tan\delta$) of the material to observables. The two key parameters in this parallel combination are the capacitance, C, and conductance, G. Parameter C is due to the presence of the induced electric field inside the filling between the two electrodes, while element G is mainly due to the imperfection of the material. In practice, these two quantities can be measured by using either an RX or an LRC meter. Once the C and G parameters are known, the following set of equations can be used to extract the permittivity, ϵ', and the loss tangent, $\tan\delta$:

$$\frac{C = \epsilon' A}{D} \tag{1}$$

$$\epsilon' = \frac{C}{C_0} \tag{2}$$

$$\tan\delta = \frac{G/\,C_0}{\omega\,\epsilon'} \tag{3}$$

where A and D are the cross section and thickness of the filled parallel plate capacitor, respectively, and C_0 is the free-space capacitance.

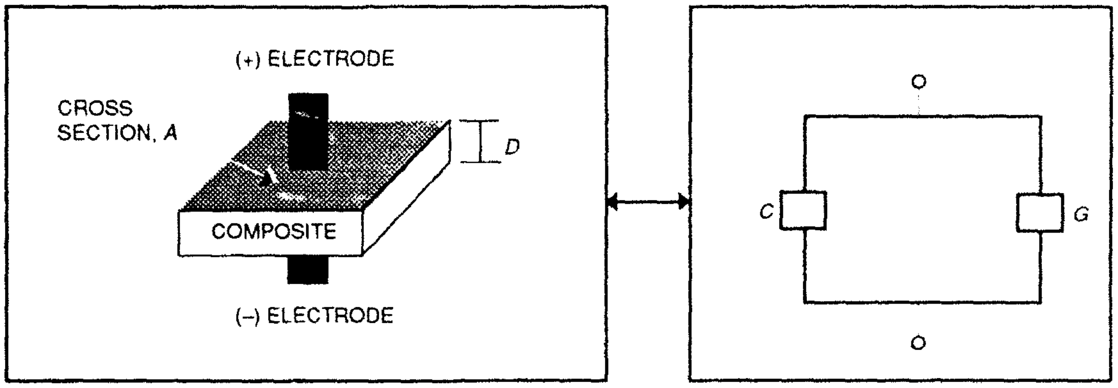


Figure 1. Filled parallel plate capacitor and its equivalent model.

Measurements of candidate off-the-shelf materials were made with a Hewlett Packard 250B RX meter and a user-designed test fixture. The RX meter permits measurement over the frequency range from 500 kHz to 250 MHz. Two laminates were used to validate the test setup. The first sample was an RT/Duroid type 6006 copper-clad laminate. Table 1 shows the measured data at different frequencies. As can be seen, the dielectric constant is between 6.17 and 7.10, depending on the operating frequency. Using the accepted value for a dielectric constant of this material (6.15), an error of 0.3% to 15% was calculated.

Table 1. Dielectric constant and loss tangent measured using the parallel plate method.

	RT/Duroid 6006		RT/Duroid 5880	
Frequency (MHz)	Dielectric Constant	Tan δ	Dielectric Constant	Tan δ
2	6.17	0.0012	2.19	0.0069
10	6.16	0.0063	2.16	0.0014
20	6.13	0.0126	2.16	0.0007
30	6.20	0.0186	2.20	0.0005
40	6.30	0.0244	2.23	0.0003
50	6.31	0.0305	2.22	0.0003
60	6.45	0.0358	2.27	0.0002
70	6.59	0.0409	2.30	0.0002
80	6.74	0.0457	2.34	0.0002
90	6.90	0.0502	2.38	0.0001
100	7.10	0.0542	2.44	0.0001

Similar measurements were made with an RT/Duroid type 5880 copper-clad laminate. In this case, the measured dielectric constant was 2.19 and 2.44 at 2 MHz and 100 MHz, respectively. These numbers correspond to an error of 4% to 16%. The accepted value for this particular material is 2.10. The general trend indicated that as the operating

frequency increased, the measured dielectric constant also increased for both laminates. This behavior is somewhat unexpected because the measurements were made at low frequencies, where the permittivity is generally thought to be independent of frequency. A comparison between our measured data and the existing values showed a maximum discrepancy of 15% and 16% for type 6006 and type 5880, respectively. An experimental accuracy of 5% should be achievable. The larger error is believed mainly due to the test fixture used in the experiment. At this time, a new test fixture design is under consideration.

COAXIAL LINE

The test fixture shown in figure 2a used the coaxial line method to measure the material dielectric constant and loss tangent. This sample holder was in the form of a coaxial transmission line, and the material sample under test must be made to fit tightly in the holder. The network analyzer was then used to measure the S-parameters of the equivalent two-port linear network (figure 2b) by comparing the incident signal with the transmitted and reflected signals. S-parameters were used to express measurement results mainly because they provided a simple notation for representing the device response. In order to minimize the effect of the loss and phase shift in the network between the sample and the measurement reference planes, the length of the 50-Ω sample holder was made the same as that of the sample. The optimum length of sample material is about $\lambda_g/4$. Once the S-parameters are known, the transmission and reflection coefficients (T, Γ) can be computed, leading towards the determination of the material dielectric constant and loss tangent. The following set of equations can be used to extract T and Γ[1] :

$$\Gamma = K \pm (K^2 - 1)^{1/2} \tag{4}$$

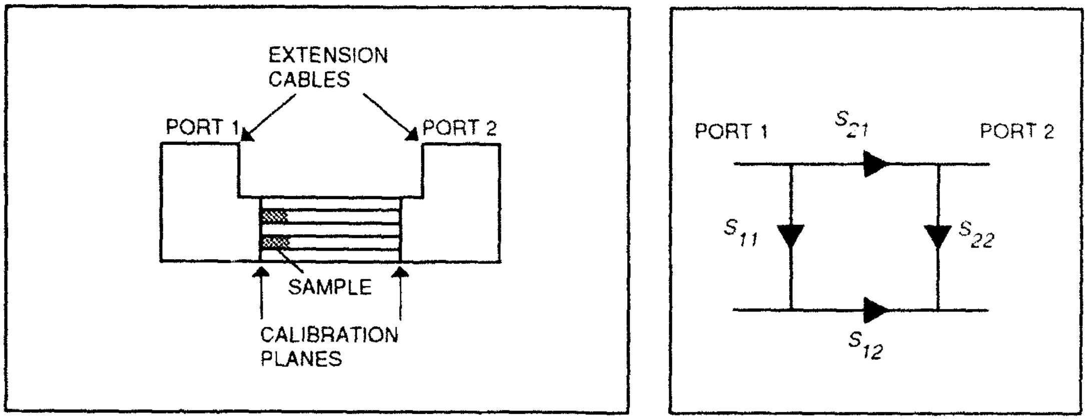
$$K = \frac{(S_{11}{}^2 - S_{21}{}^2) + 1}{2\, S_{11}} \tag{5}$$

$$T = \frac{(S_{11} + S_{21}) - \Gamma}{1 - (S_{11} + S_{21})\Gamma} \tag{6}$$

$$\epsilon = \left\{ \frac{[(c / \omega d) \ln (1/T)]^2}{[(1 + \Gamma) / (1 - \Gamma)]} \right\}^{1/2} \tag{7}$$

where c is the velocity of light in free space, ω is the angular frequency, and d is the length of the material sample. ϵ is a complex quantity, the real part (ϵ') represents the dielectric constant, and the imaginary part (ϵ'') can be used to compute the loss tangent:

$$\tan\delta = \frac{\epsilon''}{\epsilon'} \tag{8}$$



(a) Coaxial sample holder. (b) S-parameter flowgraph.

Figure 2. Text fixture.

The coaxial line method was validated through a Rexolite sample measurement. The length of the coaxial sample was 455.0 mils, and the radius of the inner tube was 60.0 mils. Swept measurement was made with a Hewlett Packard 8510 network analyzer. Figure 3 shows the measured dielectric constant of the Rexolite in the frequency range from 400 MHz to 2.0 GHz. A typical value for the dielectric constant of the material over this band is about 2.46. The accepted value for Rexolite is 2.56.

Five composites were tested: E-glass/100, E-glass/201, S-glass/202, C-glass/203, and ECE-glass/204.* In all cases, Vinylester was the resin. The dimensions and cut patterns of these samples were the same as those of the Rexolite. In all cases, the fibers were oriented parallel to the slab surface. Figure 3 shows the measured dielectric constant for the E-glass/100, E-glass/201, and E-glass/202. For the E-glass/100 material, the measured dielectric constant varied between 3.91 and 4.3, depending on the sample that was used for the measurement. For other materials, particularly E-glass/201 and S-glass/202, the measured dielectric constant was about 4.7 and 3.78, respectively. In all cases, the response was invariant with frequency. Figure 4 shows the measured loss tangent of the above materials. For the remaining materials, namely, C-glass/203 and ECE-glass/204, the same procedure was carried out; however, this method failed to yield valid data. This failure was due to the fact that these two materials are lossy, and the method is designed for lossless materials.

* E-glass/100: 8 ply of 50 oz, woven
E-glass/201: 20 ply of 24 oz, woven
S-glass/202: 20 ply of 24 oz, woven
C-glass/203: 23 ply of 24 oz, carbon
ECE-glass/204: 7 ply of 24-oz E-glass, 8 ply of 24-oz carbon, and 7 ply of 24-oz E-glass

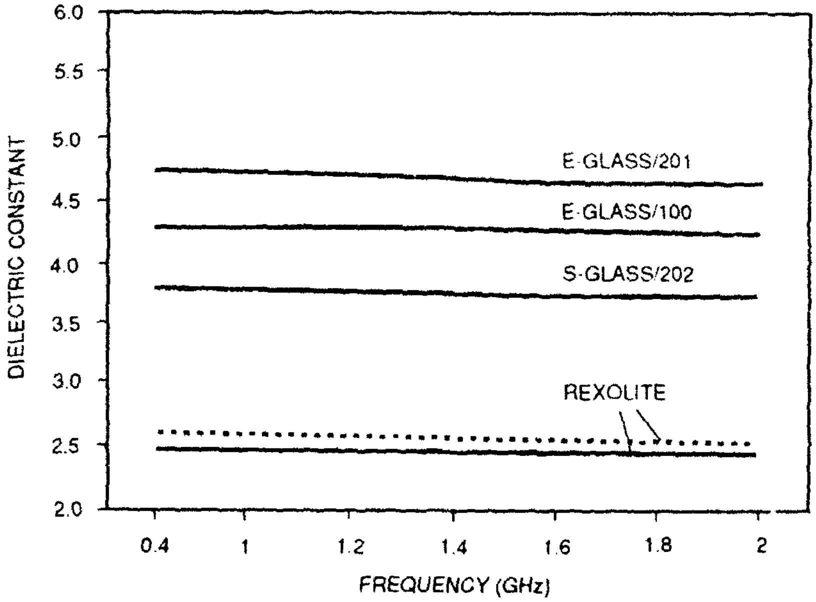


Figure 3. Dielectric constant versus frequency.

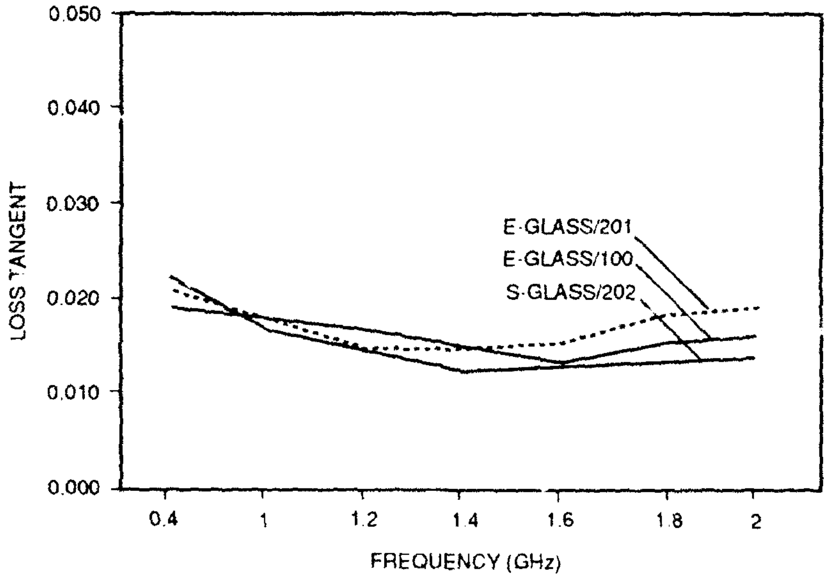


Figure 4. Loss tangent versus frequency.

MICROSTRIP RESONATOR

The EM properties of the material can also be characterized by using the microstrip resonator method. In this approach, a rectangular metal strip of width W and length L was printed on one side of a slab of thickness H, as shown in figure 5. To measure the resonant frequency of the resonator, a CW signal was injected into the resonator through a short microstrip line, causing the device to resonate at frequencies that corresponded to resonator multiple half-wave lengths. Once the resonant information was obtained, an algorithm based on the Fourier domain analysis [2–3] was then used to compute the dielectric constant of the material. In the Fourier domain, the characteristic equations used to solve the real part of permittivity ϵ' are

$$\sum_{m=1}^{M} T_{im}^{(1,1)} C_m + \sum_{m=1}^{N} T_{im}^{(1,2)} D_m = 0 \qquad i = 1, 2, 3, \ldots, N \tag{9a}$$

$$\sum_{m=1}^{M} T_{im}^{(2,1)} C_m + \sum_{m=1}^{N} T_{im}^{(2,2)} D_m = 0 \qquad i = 1, 2, 3, \ldots, M \tag{9b}$$

with

$$T_{im}^{(1,1)}(k_0) = \sum_{n=1}^{\infty} \int_0^{\infty} \tilde{J}_{zi}(\alpha,\beta)\, \tilde{G}_{zz}(k_0,\alpha,\beta)\, \tilde{J}_{zm}(\alpha,\beta) d\beta \tag{10}$$

$$T_{im}^{(1,2)}(k_0) = \sum_{n=1}^{\infty} \int_0^{\infty} \tilde{J}_{zi}(\alpha,\beta)\, \tilde{G}_{zy}(k_0,\alpha,\beta)\, \tilde{J}_{ym}(\alpha,\beta) d\beta \tag{11}$$

$$T_{im}^{(2,1)}(k_0) = \sum_{n=1}^{\infty} \int_0^{\infty} \tilde{J}_{yi}(\alpha,\beta)\, \tilde{G}_{yz}(k_0,\alpha,\beta)\, \tilde{J}_{zm}(\alpha,\beta) d\beta \tag{12}$$

$$T_{im}^{(2,2)}(k_0) = \sum_{n=1}^{\infty} \int_0^{\infty} \tilde{J}_{yi}(\alpha,\beta)\, \tilde{G}_{yy}(k_0,\alpha,\beta)\, \tilde{J}_{ym}(\alpha,\beta) d\beta \tag{13}$$

with $\tilde{G}$ being the dyadic Green's function of the structure and $\tilde{J}_{y,z}$ corresponding to the current distribution on the resonator. Equation 9 is solved simultaneously by setting the determinant of the coefficient matrix equal to zero and searching for the root. The resulting root is then used to compute the dielectric constant of the material.

Since this measurement is a two-port technique, in addition to the resonance information, the transmission and reflection coefficients may also be obtained. Identical microstrip lines were used to couple the energy in and out of the resonator. Additionally, an appropriate gap size at both ends of the resonator achieved consistency. The loss tangent was obtained directly from the measured transmission and reflection coefficients.

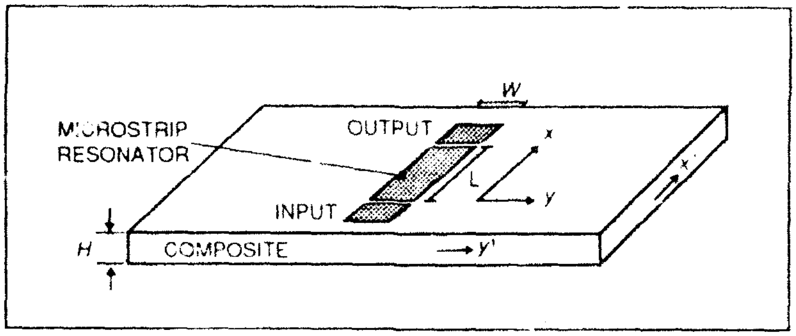


Figure 5. Physical layout of a microstrip resonator.

A Hewlett Packard 8510 network analyzer was used for the microstrip resonator measurements. To validate the technique, a resonator printed on Teflon was measured and compared to the published data. Four different orientations were tested. In the first two orientations (x, y) the direction of the E-field was perpendicular to the slab top and bottom surfaces, and for x', y' the field was parallel. Table 2 shows the experimental data measured at 600 MHz. The relative dielectric constant and loss tangent of Teflon varied from 2.09 to 2.11 and from 0.008 to 0.010, respectively, depending on the direction of the E-field. The accepted value for dielectric constant and loss tangent of Teflon is 2.10 and 0.008. The experimental error for the permittivity of this particular material is about 0.5 %.

Table 2. Dielectric constant and loss tangent measured using the microstrip resonator method.

Type	x'	y'	x	y
E-glass/100	4.07/0.014	4.08/0.015	5.07/0.018	4.73/0.022
E-glass/201	6.32/0.090	4.83/0.080	5.67/0.080	5.99/0.092
S-glass/202	3.75/0.019	3.65/0.022	4.51/0.024	4.52/0.025
ECE-glass/204	-	-	5.00/ -	5.09/ -
Teflon	2.10/0.010	2.10/0.009	2.11/0.010	2.09/0.008

Next, the microstrip resonators printed on different materials were measured. The same five composites that were considered in the previous section were the materials under test. Table 2 displays the measured dielectric constant along with the loss tangent of each material. For E-glass/100, ϵ' varied from 4.73 to 5.07, depending on the E-field orientation. Similar anisotropic behavior was also observed in the E-glass/201 and S-glass/202. The general trend indicated that the E-glass/201 composite was more

anisotropic than the E-glass/100. The loss tangent of the E-glass/201 was also higher than the E-glass/100.

In contrast to the E-glass/201material, the S-glass/202 has properties that are quite unique. When the direction of the electric field was parallel to the slab top and bottom surfaces, the dielectric constant varied from 3.75 to 3.65. In the other configuration, particularly when the field was perpendicular to the surfaces, a value between 4.51 and 4.52 was measured.

The fourth material tested using this method was the E-glass/C-carbon/E-glass type. Under one arrangement, the material became very lossy, mainly due to the direct exposure of the carbon layer beneath the metal strip. The microstrip resonator method failed to work in this case. However, for the other E-field arrangement, a dielectric constant value between 5.00 and 5.09 was measured. When the C-glass/203 was inserted into the test set as a sample, the microstrip resonator method, like the other methods, failed to yield valid data. This failure was due to the fact that the C-glass/203 is a very lossy material. The difficulty of making measurements on lossy materials is somewhat expected because the microstrip resonator method is intended mainly for lossless materials.

TIME DOMAIN

Figure 6 shows the time-domain test setup that was used [3]. The integrated test setup consisted of a pulser, a directional coupler, and a bounded wave simulator (BWS). In this technique, the pulser delivered a 4.5-kV/120-ps rise time pulse to the object under test inside the BWS. The time waveshape signal was then collected and translated into the frequency domain through a Fast Fourier Transform (FFT) processor. After the translation, the resulting signal spectrum was then compared to the spectrum from a metal plate of the same size and shape to derive the input reflection coefficient $\Gamma(f)$:

$$\Gamma(f)^i = M(f)^d / M(f)^m \tag{14}$$

where $M(f)^d$ is the returned amplitude from the material sample under test and $M(f)^m$ corresponds to the returned amplitude from the metal plate. Once the input reflection coefficient was collected, the dielectric constant of the material was extracted by manipulating the following set of expressions:

$$\Gamma(f)^i = (Z - \eta_1)/(Z + \eta_1) \tag{15}$$

with

$$Z = \eta_2 \frac{\eta_3 + \eta_2 \tanh \gamma_2 d_2}{\eta_2 + \eta_3 \tanh \gamma_2 d_2} \tag{16}$$

$$\eta_1 = \eta_3 = (\mu_0/\epsilon_0)^{1/2} \tag{17}$$

$$\eta_2 = (\mu_0/\epsilon'\epsilon_0)^{1/2} \tag{18}$$

$$\gamma_2 = \omega(\mu_0\,\epsilon'\epsilon_0/2)^{1/2} \tag{19}$$

where d_2 is the thickness of the sample, γ_2 is the propagation constant in the sample, and η_1 and η_3 are the intrinsic impedances. Limited work was done using this method. In the experiment, an E-glass/201 sample of size 1 × 1 inches was used. The sample under test was mounted upright with the slab facing the source inside the bounded wave simulator. The pulser delivered a sharp rising pulse and the signal was collected through the directional coupler. The time waveshapes from the dielectric plate and from the metal plate were then translated into frequency domain to extract the dielectric constant of the material. Figure 7 shows a typical reflection coefficient measurement from 100 MHz to 900 MHz. The corresponding relative dielectric constant is also displayed in figure 7. The dielectric constant data show some agreement to accepted values; however, the values seems to be low at 200 MHz and 300 MHz

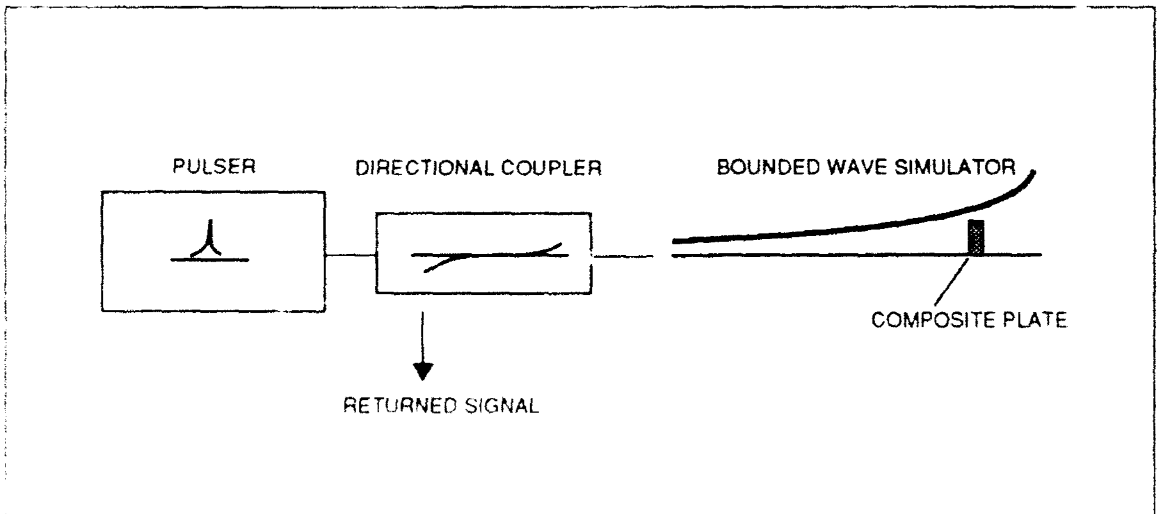


Figure 6. Time-domain test set.

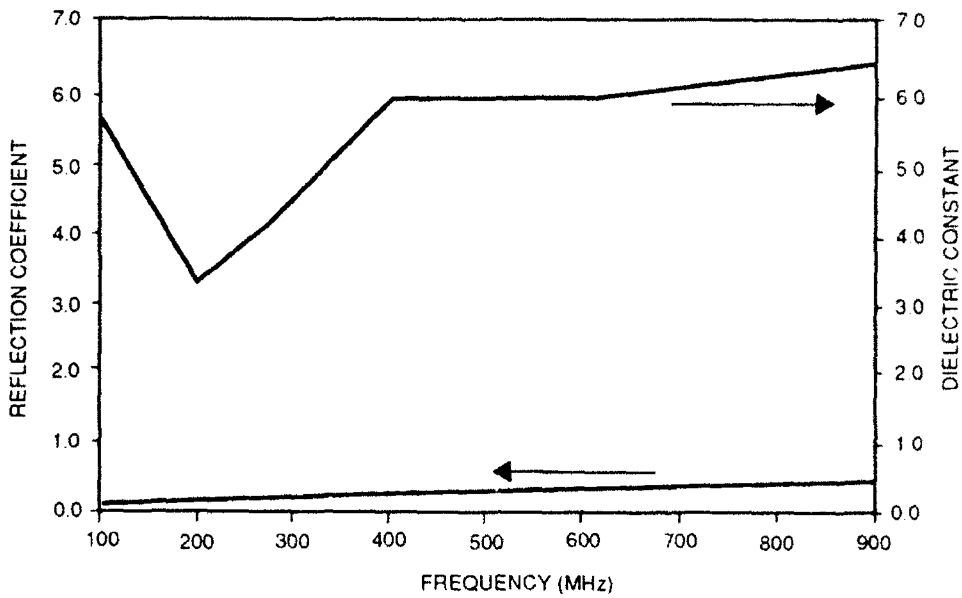


Figure 7. Reflection coefficient and dielectric constant versus frequency.

CONCLUSIONS AND RECOMMENDATIONS

In the above sections, four different methods were examined that may be used to measure EM properties of the composite materials. The conventional parallel plate method is normally valid for frequencies up to 500 MHz. In our case, even though the operating frequency is well within the range for accuracy, the experimental data still show about 10% to 15% off the accepted values. This discrepancy is believed mainly due to the test fixture that was used in the experiment. A new test fixture needs to be developed in order to improve the measurement accuracy, particularly a test fixture that has minimal stray capacitance. Additionally, a study between different sample sizes needs to be carried out to determine the optimal sample size for accuracy.

The coaxial line method has been proven to be a good candidate for measuring dielectric materials. The main advantage of this method is that swept measurements can be made simultaneously without any modification to the test setup. This method may also be used to extract the complex permeability (μ' and μ'') of the magnetic materials. Since the sample is in cylindrical form, the electric field inside the sample is radial, a potential problem may arise when the measurement is made with composite materials. With current technology, most of the composite materials are woven; as a result, they are more or less anisotropic. An evaluation of ultilizing this method for measuring anisotropically composite materials needs to be conducted.

Measurements based on the microstrip resonator have proven to be reliable. The procedure is very straightforward to implement. Since this method is a full-wave method, the data are not only valid at low frequencies but also at high frequencies. In the above

experiment, the experimental data agree within 1% of the published data when Teflon was used as a sample. This method may also be used to characterize anisotropic substrates, since the orientation of the resonator can be laid out accordingly. Even though this technique is discrete, it is more than appropriate, since the dielectric constant materials do not expect to change considerately over the frequency band up to 40 GHz.

The BWS has been used to measure the frequency and time-domain response of complex systems. The use of the BWS in the time domain to determine the frequency-domain reflection coefficient and permittivity is novel. Since the measurements are done in time domain, the dielectric constant of the material as a function of frequency may be derived from the FFT of the returned pulse signal. An initial assessment of the practicalities of the method shows that wide-band measurements may be possible with this method. However, modifications to the existing setup need to be made to improve the measurement accuracy in order to reduce this method to practice.

REFERENCES

[1] Hewllet Packard note 8510-3, "Materials Measurement," 1985.

[2] T.Q. Ho, B. Beker, Y.C. Shih, and C. Chen, "Microstrip Resonators on Anisotropic Substrates," *IEEE Trans. on Microwave Theory and Techniques*, Vol. MTT-40, pp. 762-765, Apr 1992.

[3] A. G. Page, C. A. Deneris, J. W. Rockway, and J. H. Schukantz. "Transient Scattering Response of Several Airborne Targets," Technical Document 2249, Naval Command Control and Ocean Surveillance Center, San Diego, CA, Mar 1992.

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13. ABSTRACT *(Maximum 200 words)*

This report describes four different techniques that may be used for measuring the electromagnetic properties of composite materials. Experimental data obtained from each method are presented. The advantages and disadvantages of each method are also discussed.

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